PREDICTION OF FRANCIS TURBINES EFFICIENCY ALTERATION BY TRAVELLING BUBBLE CAVITATION

Christophe Arn   François Avellan   Philippe Dupont

LMH-IMHEF-EPFL
33, av. de Cour, CH–1007 Lausanne, Switzerland
Email: christophe.arn@epfl.ch

Abstract

The setting level of a hydraulic machine, specially for low head machines, is decided with respect to the possible alteration of the efficiency due to the cavity development. This alteration can easily be noticed by plotting the evolution of the efficiency η as a function of the Thoma number σ leading to the so-called $\eta - \sigma$ cavitation curves. In order to protect the efficiency at the best operating point against the travelling bubbles effects, the *IEC* norms suggest some measures relating to turbines standards cavitation tests. A prediction method of the efficiency drop due to the outlet travelling bubble cavitation is then so needed to guide the runner geometry design in the first state of the project. The main objective of this paper is the presentation of a cavitating pressure field prediction method in the runner in order to calculate the corresponding efficiency alteration.

Keywords: CAVITATION, FRANCIS TURBINE, EFFICIENCY, BUBBLES

1 Introduction

The setting level of a turbomachine is one of the most critical parameters of its design. The travelling bubble phenomenon is the cause of many problems like the alteration of the performances of the machine and also the possible erosion of some parts of the installation. This setting level is usually defined by the value of the Thoma number σ. In the particular case of the best operating point of a Francis turbine, an alteration of the efficiency appears beyond a typical value of the Thoma number σ_0. Although the effects of such cavitation developments have been treated by many authors such as Avellan and Henry (1984) or Gindroz (1991), no methods are available at the moment in order to predict the efficiency alteration according to the setting level. Some statistical studies are proposed by Knapp *et al.* (1970), Creager and Justin (1950), Vivier (1966) or Siervo and Leva (1976). These studies allow to determine a value of the acceptable Thoma number σ depending on the specific speed[1] of the machine ν. The dispersion of the different curves presented in the Figure 1 shows that this type of studies is not reliable in order to define accurately the setting level of the machine. The aim of the actual studies concerns refurbishment projects for which the setting level of the machine is imposed by the existing installation. A prediction method of the critical Thoma number σ_0 of the runner is then necessary to ensure an optimization of the runner efficiency.

[1]The specific speed ν of a hydraulic turbine is a non-dimensional coefficient which characterize the geometry of the runner. It depends on the specific energy of the machine E, the discharge Q and the rotational speed ω: $\nu = \frac{\omega}{2^{3/4}\pi^{1/2}} \frac{Q^{1/2}}{E^{3/4}}$.

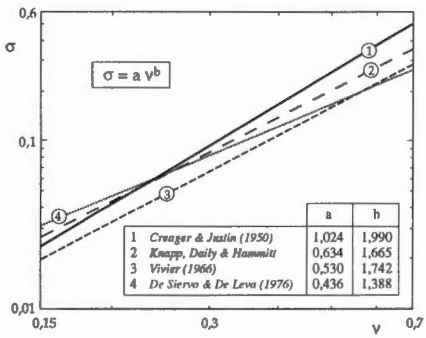

Figure 1: Statistical values of admissible Thoma number σ in function of the specific speed ν of a Francis turbine

2 Bubbles influence on the blade

If we consider the global transfer of energy between the flow and the runner, we can suppose the alteration of the efficiency to be only due to the modification of the energy transfer from the flow to the blades. The mechanical and volumetric losses are not modified and the global alteration of the efficiency can be described by the energetical efficiency drop. Some previous experiments show that the alteration of this transfer is caused by the limitation of the pressure field at the value of the vapour pressure p_v. These experiments were carried out with a Francis turbine model instrumented by absolute pressure transducers and the results presented and discussed by Arn *et al.* (1996). The direct contact between the blades wall and the vapour phase is the main factor of the efficiency alteration by modifying the pressure acting on the blades. This contact is clearly illustrated in the Figure 2. This image is realized with a light intensification *CCD* camera mounted on the test section of the *IMHEF* cavitation tunnel. We can observe that the bubbles have a serious trend to flatten against the blade wall. The typical shape of the bubbles in evolution on the blade is then hemispherical.

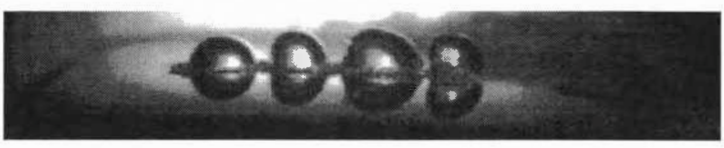

Figure 2: Vizualisation of travelling bubble development on the suction side of a 2-D NACA009 blade. $C_{ref} = 20\,m/s$. $\chi = 0,3$.

These deformations were observed by Ceccio and Brennen (1991) and Kuhn (1994) and supposed by Lecoffre and Danel (1977) and Menoret and Blayo (1988). These last authors have proposed a simple model for the prediction of the pressure field with hemispherical bubbles. This model is based on the bivalency of this particular pressure field and supposes that the pressure is weighted by the probability β that the corresponding point is under a bubble:

$$p(x,t) = \beta(x,t)p_v + (1 - \beta(x,t))p_0(x) \tag{1}$$

where $p_0(x)$ is the steady value of the static pressure without cavitation and $\beta(x,t)$ the weight factor. Then the mean value of the pressure during a time τ is given by:

$$\overline{p(x,t)} = p(x) = \overline{\beta(x,t)}p_v + (1 - \overline{\beta(x,t)})p_0(x) \qquad \text{with} \qquad \overline{\beta(x,t)} = \frac{1}{\tau}\int_0^\tau \beta(x,t)dt \quad (2)$$

The numerisation and the processing of images, obtained with the same set-up as the one used for the example illustrated on the Figure 2, allow the quantification of the contact area between the vapour phase and the blade. By comparing these measured areas with the estimated values of hemisphere obtained using the radius computed by the resolution of the Rayleigh-Plesset equation, one can observe a very good concordance. The computation of the hemisphere radius with this equation represents a good approach for the determination of a typical contact area on which the probability β mainly depends.

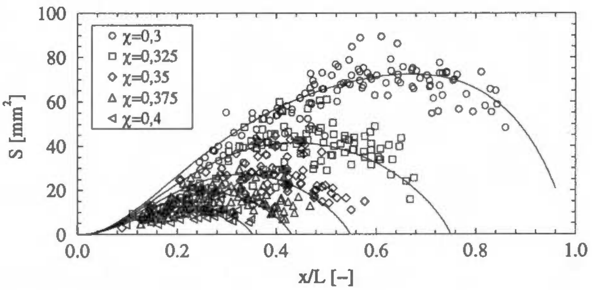

Figure 3: Bubble contact surface area on the suction side of a 2-D NACA009 blade. $C_{ref} = 20\,m/s$

The initial value of the bubble radius is not very important for these comparisons. Indeed, in the range of the active nuclei, the maximum sizes of the bubbles and the collapse locations are very similar. These last values are depending on the activating pressure instead, which is characterized by the cavitation factor $\chi = (p_{ref} - p_v)/\frac{1}{2}\rho C^2$. As a first approach, we can consider that the weight factor β is equal to the contact surface ratio between the vapour phase and the blade. This ratio can easily be determined by supposing a compact repartition of the activated bubbles. This hexagonal scheme is illustrated in Figure 4. The value of β is then function of the radius of the bubbles and their density, which mainly depends on the critical nuclei concentration N_c. The value of the weight factor is given by the following relation:

$$\overline{\beta(x,t)} = \sqrt[3]{\frac{2}{\sqrt{3}}} N_c^{2/3} \pi R^2(x) \quad (3)$$

The reference pressure p_0 of the cavitation free field is obtained with a 3D Navier-Stokes computation code. The results of the Navier-Stokes computation allow to determine, for each mesh point of the suction side, the streamlines upstream. The weight factor β is finally determined with the computation of the bubble radius along these streamlines. The new pressure field obtained is processed in order to compute the new torque and then the value of the efficiency drop. The method is summarized in the scheme illustrated in Figure 5.

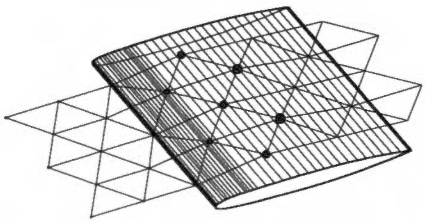

Figure 4: Hexagonal repartition of active nuclei on a 2-D blade

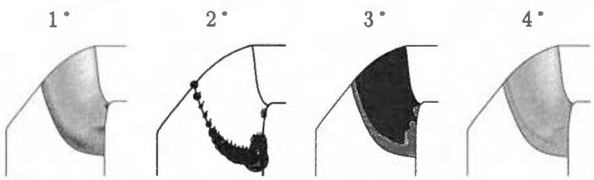

Figure 5: Cavitating pressure field computation method: 1° Cavitation free pressure field computation. 2° Bubble radius determination on each mesh point. 3° Weight factor $\overline{\beta(x,t)}$ computation. 4° Modification of the pressure field. H_{ref}=10m and σ =0,03

3 Results and discussion

The test case is a Francis turbine model with a specific speed $\nu = 0.33$ at the best efficiency operating point. The nuclei distribution used for the computation is determined in this test case by the measured inception of the first bubbles on the blade. The first bubbles are generated by the greatest nuclei of the test water. The observation of the cavitation inception in the model allows to determine the setting level σ_i and then the corresponding cavitation factor $\chi_{B,i}$. The radius of these greatest nuclei, representing the susceptibility of the test water, allow to quantify all the nuclei distribution by supposing an exponential repartition. The meridional view of the weight factor on the blade is illustrated on Figure 6 for a high value of the Thoma number and the value of 0,04 corresponding to an efficiency alteration of two percents.

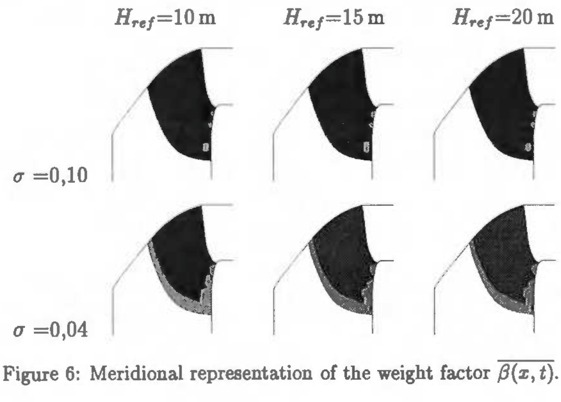

Figure 6: Meridional representation of the weight factor $\overline{\beta(x,t)}$.

We can observe in these representations that the pressure field is mainly modified at the outlet of the blades and near the band. The reason for this bubble development along the runner band is a low pressure located at the leading edge for this operating point. Some observations carried out in the full-scale machine have shown a severe erosion in this zone. The analysis of the weight factor distribution shows very well the bivalency of the pressure field. Moreover, this tendency will be increased in the case of the full-scale machine. A determination of the pressure field alteration supposing a threshold by the vapour pressure in the low pressure zones is not sufficient, indeed, the effects of the bubbles stretch as far as the collapse zone. The representation of the pressure field modification can be accurately described only if the vapour phase repartition is exactly defined. Obviously a little low pressure zone is capable to activate an important development of bubbles downstream and the threshold of this zone by p_v is not sufficient to predict the right cavitating pressure field. The evolution of the weight factor β near the band of the runner is therefore very representative. The computation of the bubbles evolution in the runner is thus the only solution to predict the pressure modification on all the blade with enough accuracy. The different curves finally obtained using our method are presented in Figure 7. The study of these curves shows that the alteration of the efficiency is very well described. The particular values of the standard Thoma number[2] σ_s and the one percent Thoma number[3] σ_1 are predicted with a mean accuracy of three percent.

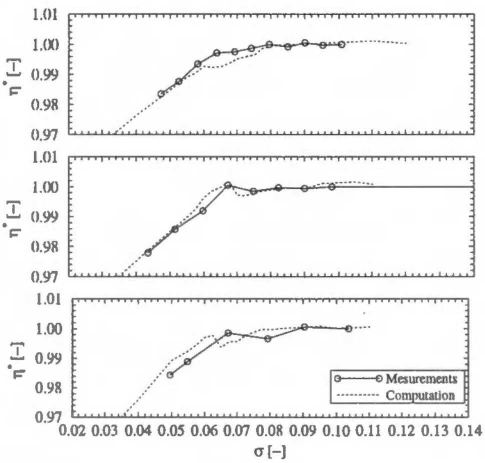

Figure 7: Computed efficiency curves compared with the measurements. From top to bottom: H_{ref}=20m, 15m, 10m

The nuclei distributions used in these computations are very different from the measured one in the test rig. The water sampling and the measurements carried out with a Venturi nuclei counter do not allow the characterization of such great nuclei. Indeed, the size of the active nuclei with such activation pressure values is typically included in the range from 10 up to 100 μm. Moreover, the size influence of the nuclei is not so important for the efficiency drop provided that they are activated. The application of our method

[2]The standard Thoma number σ_s is defined by the intersection of the line corresponding to the altered part of the curve and the value of the efficiency without cavitation.

[3]The one percent Thoma number value σ_1 is the particular value of the Thoma number corresponding to an efficiency alteration of one percent.

implies the knowledge of the accurate concentration of nuclei in the zone of their activation. However, the full-scale values of mean nuclei concentrations are clearly sufficient to reach the saturation condition in the runner and then to ensure a good evaluation of the cavitating pressure field.

4 Conclusion

The main objective of this work is the development of a numerical method capable to predict the threshold of the efficiency alteration of the Francis turbines with enough accuracy. The main possibilities are experimental at present and the elaboration of such a tool is then very interesting in the global context of the Francis runner numerical design. The presented method allows to compute the $\eta - \sigma$ curves from the results of the free cavitation flow computation using any available CFD code. The initial pressure field is processed and modified in order to compute a new value of the torque with the standard post-processor of the used code. The application of this modelling to different runners in the complete range of the specific speed concerning the Francis turbines will be the next stage of this work. The study of the main parameters influence, like the local nuclei concentration in the bubble activation zones, will be then also accurate. Theses perspectives represent the final expression of this promising development.

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